ANALYSIS OF POSTTENSIONED ANCHOR BOND-STRESS DISTRIBUTION POINT MARION LOCK, MONONGAHELA RIVER

by

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In February 1989, the US Army Engineer Waterways Experiment Station was asked by the US Army Engineer District, Pittsburgh, Ohio River Division (ORD), US Army Corps of Engineers, to perform a structural and stability analysis of key monoliths of the Point Marion Lock, Monongahela River. Plans call for anchoring the existing land wall to underlying rock strata to resist sliding forces and overturning moments that developed following removal of backfill to create the cofferdam necessary for construction of the new lock facility. ORD requested that a finite-element analysis of representative monoliths be performed to determine the internal stresses resulting from the application of the anchoring forces and backfill removal. This report addresses only the analyses and modeling of posttensioned anchor bond-stress mechanism. Based on the results of the survey of recent developments in the state of the art of posttensioned anchor bond-stress calculation, the equations proposed by Cousins et al., were used to predict the bond-stress distribution along the secondary grouted anchors. The results of the finite-element analyses   (Continued)

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19.   ABSTRACT (Continued).

presented clearly show that the bond-force equations used provide a rational and consistent method for predicting bond-force distribution. The analyses show that neither the estimated compressive strength of the grout and concrete nor the estimated shear strength along the grout-concrete interface were exceeded.

PREFACE

The analyses described in this report were conducted for the US Army Engineer District, Pittsburgh (ORP). Authorization was given by DA Form 2544, CEORPD-ED-89-48, dated 21 Feb 1989. The funds for publication of this report were provided by the Concrete Technology Information Analysis Center (CTIAC); it is CTIAC Report No. 85.

The analyses were performed at the US Army Engineer Waterways Experiment Station (WES) by personnel of the Structures Laboratory, under the general supervision of Messrs. Bryant Mather, Chief, and J. T. Ballard, Assistant Chief. Direct supervision was provided by Mr. K. L. Saucier, Chief, Concrete Technology Division (CTD). Technical direction was provided by Mr. Michael I. Hammons of the Engineering Mechanics Branch, CTD. This report was prepared by Messrs. Donald M. Smith and Michael I. Hammons, Engineering Mechanics Branch, CTD. The authors acknowledge Ms. Sharon B. Garner, Mr. Brent Lamb, and Ms. Linda Mayfield of the Engineering Mechanics Branch, CTD, for their help during this investigation. This report was published by the Information Products Division, Information Technology Laboratory, WES.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	25.4	millimetres
kips (force)	4.448222	kilonewtons
kips (force) per square inch	6.894757	megapascals
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

ANALYSIS OF POSTTENSIONED ANCHOR
BOND-STRESS DISTRIBUTION
POINT MARION LOCK, MONONGAHELA RIVER

PART I: INTRODUCTION

Background

1. In February 1989, the US Army Engineer Waterways Experiment Station was asked by the Ohio River Division (ORD), Pittsburgh District (ORP), Corps of Engineers, to perform a structural and stability analysis of key monoliths of the Point Marion Lock, Monongahela River. The land wall of the existing lock will be used as the cofferdam for the construction of the new Point Marion Lock, which will be landward and parallel to the existing lock. Plans call for anchoring the existing land wall to underlying rock strata to resist sliding forces and overturning moments developed due to removing the backfill. The anchor system consists of one vertical anchor and two inclined anchors at intervals of nominally 7 to 9 ft along the long axis of the lock. The ORD requested that a finite element analysis of representative monoliths be performed to determine the internal stresses resulting from the application of the anchoring forces and backfill removal.

2. A typical landwall monolith and foundation is shown in Figure 1. A basic description of the planned anchoring procedure follows. An 8-in. diameter hole is drilled at a predetermined location in the lock wall. The hole passes through the lock wall into the underlying rock strata. A stranded steel anchor is then grouted into the foundation. After the primary grout has reached sufficient strength to secure the anchor to the foundation, the anchor is then tested to 75% of its ultimate strength by jacking against the surface of the lock wall. After this initial stressing, the jacking load is reduced to 60% of the anchor's ultimate strength. At that time, grout is injected into the hole surrounding the anchor in the lock wall. After the secondary grout has attained sufficient strength, the jacking force is reduced and locked off at 10,000 lb. The jacking force is thereby distributed into the interior of the lock wall by the secondary grout.

3. To effectively address the problems associated with excavation and anchoring monoliths of the Point Marion Lock, three interrelated analyses tasks were defined:

Task 1. Finite-element analysis of the structure-foundation system.

Task 2. Concrete and foundation material modeling and analysis of anchor-load distribution.

Task 3. Finite-element analysis of foundation conditions.

This report addresses only the analyses and modeling of the transfer bond-stress mechanism.

Objective

4. The objective of this investigation was to conduct a finite-element analysis to determine the magnitude and distribution of forces along the lengths of the anchors during the two stages of tensioning force application and secondary grouting.

Scope

5. To accomplish this investigation, a III-phase plan was developed. The originally developed plan is presented below.

Phase	Investigation Plan
I	Selection of material properties based on engineering judgment with attempts to provide expected bounds on key material properties.
II	Selection of bond-force distribution function based on current experimental, analytical, and computational methods.
III	Analysis of stress distribution within a generic monolith-anchor system due to a force distribution based on the results of Phase II. Both linear and non-linear analyses were performed.

Figure 1. Typical landwall section

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PART II: GENERAL DESCRIPTION OF ABAQUS FINITE-ELEMENT PROGRAM

6. The ABAQUS Finite-Element Program was used for the Point Marion Lock Anchor Bond-Stress Distribution Studies. This choice was based upon the availability, flexibility,and capability requirements necessary to complete this investigation within the overall project constraints.

7. ABAQUS, developed by Hibbitt, Karlsson, and Sorensen, Inc., is a general-purpose structural analysis program. The theoretical formulation is based on the finite-element stiffness method with some hybrid formulations included as necessary. The program includes both user and automatic control of solution step size. Input is free format, key worded, and makes use of set definitions for easy cross reference. A broad element library is included in ABAQUS and any combination of elements can be used in the same model. A wide variety of constitutive models is also provided in ABAQUS, and these models can essentially be used with any element type. Both linear and non-linear analyses can be performed with ABAQUS. Specific details of analysis type, constitutive model, element type, and boundary conditions will be presented in the various phases of this report.

PART III: INPUT DATA AND MODELED PARAMETERS

General

8. This section describes the input data and modeled parameters used in all analyses conducted for this investigation. It was understood that a complete and accurate assessment of the internal stresses resulting from the application of the anchoring forces and backfill removal would require a complete and accurate set of material properties for both the lock and the foundation. However, due to project time constraints, these properties were not available. Therefore, properties were selected for the analyses based on engineering judgment to provide expected bounds on key material properties.

Concrete Properties

9. The input data used for the mechanical properties of concrete were based on previous mechanical properties tests of concrete from similar structures on the upper Ohio River system that were approximately the same age as the Point Marion Lock. The concrete was assumed to have an unconfined compressive strength of 2,000 psi, a modulus of elasticity of 2 X 10^6 psi, and a Poisson's ratio of 0.20 . A non-linear analysis was performed using the ABAQUS version of the Chen and Chen Inelastic Constitutive Model (1975) for concrete. The calibration parameters used in this model were chosen based on previous experience with similar concretes and recommendations in the ABAQUS Model description. These values include the following parameters which are graphically identified in Figures 2 and 3.

       (1) Initial yield point occurred at a stress of 1,200 psi and a strain of 600 millionths.

       (2) The ratio of the ultimate biaxial compressive strength to the uniaxial compressive ultimate strength was 1.16.

       (3) The ratio of tensile strength to uniaxial compressive strength was 0.09.

       (4) The ratio of the principal component of plastic strain in biaxial compression to plastic strain at ultimate

stress in uniaxial compression was 1.28.

(5) The ratio of the tensile principal stress value at cracking, in plane stress when the other non-zero principal stress component is at the ultimate compressive stress value, to the tensile cracking stress under uniaxial tension was 0.33.

Grout Properties

10. The input data used for the mechanical properties of the grout were based on previous tests and consultation with field personnel. The grout was assumed to have an unconfined compressive strength of 4,500 psi, a modulus of 2.5×10^6 psi, and a Poisson's ratio of 0.23 . The Chen and Chen Model was used to model the grout for the non-linear analysis. The calibration parameters remained the same as the concrete except that the yield stress was 2,700 psi and the strain at yield was 1,080 millionths.

Steel Properties

11. The input data used for the mechanical properties of the steel anchors were based on consultation with field personnel and manufacturer material properties information. The steel used was a 0.6-in. dia. 7-wire strand with an ultimate strength of 270,000 psi and an average modulus of elasticity of 28.5×10^6 psi. Both 12-wire and 14-wire strands were used depending on the application.

Bond-force Distribution Calculations

12. A review of the current state-of-the art in transfer of bond-stresses calculation indicated that there are four available equations. A discussion of the bond-transfer mechanism and these equations follows.

13. The tensile stress in each steel anchor strand is transferred to the surrounding grout by bond in the end region of the strand. The distance from the end of the strand over which the transfer of the effective stress,

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f_{se}, is accomplished is the transfer length, L_t. The corresponding compressive stresses in the grout are zero at the free end and increase with distance from the free end. At any section in the system, the compressive force in the grout is equal in magnitude and opposite in direction to the tensile force in the steel.

14. A number of empirical relationships for transfer length have been proposed. The American Concrete Institute (ACI, 1983) recommends the following relation for transfer bond stress alone (i.e., ignoring additional bond length for flexural bond):

$$L_t = (f_{se}/3)$$

15. A more conservative relationship for transfer bond length was proposed by Martin and Scott (1979) as follows:

$$L_t = 80d_b$$

where d_b is the diameter of a single strand.

16. The above relationships are inadequate in that neither of them consider the strength of the surrounding material into which the stresses are transferred. Zia and Mostafa (1977) developed a relationship which takes in to account both the stress in the steel and the strength in the concrete. A linear regression analysis of research prior to 1977 was used to develop the following relationship for transfer length:

$$L_t = [1.5(f_{si}/f_{ci})d_b] - 4.6$$

where

    f_{si} = initial stress in strand prior to losses (ksi)

    f_{ci} = compressive strength of concrete at transfer (ksi)

17. However, none of the these relationships provide a means for calculating the magnitude of the bond transfer stresses. At any point in the system, the bond transfer stress is simply the slope the steel stress versus length curve at that point. Cousins, et al, (1986) developed an equation based on theoretical considerations which allows for the calculation of transfer stress and transfer length. This relationship assumes that the transfer length is the sum of an elastic transfer length, L_t^e, and a plastic transfer length, L_t^p (Figure 4). In the elastic zone, bond stresses are considered to be proportional to slip between the strand and the concrete. At

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the end of the proportional section, the bond stress reaches a yield value, U_t, and is constant throughout the plastic zone to the free end of the strand. The Cousins relationship for transfer length is given by

$$L_t = \{1/2(U_t)/B\} + \{f_{se}A_s/(\pi d_b U_t)\}$$

where

B = bond-stress modulus (slope of bond-stress curve in elastic zone) psi/in

$U_t = U_t' \quad f_c'$ = transfer bond stress.

The length of the elastic bond length is given by

$$L_t^e = U_t/B,$$

with the length of the plastic transfer zone given by

$$L_t^P = L_t - L_t^e.$$

18. The constants B and U_t' can be determined from experiments. Cousins, et al, present recommended values for these constants based upon their research: for uncoated strands U_t'= 6.7 and B = 300 psi/in.

19. Using the Cousins relationships and recommended values of the constants B and U_t', a transfer bond-stress distribution was estimated. Based upon information furnished by ORP, the following parameters were input into the relations:

$$f_{se} = 164,000 \text{ psi}$$
$$f'_c = 4,000 \text{ psi}$$
$$A_s = 0.215 \text{ in}^2$$
$$d_b = 0.6 \text{ in}$$

The resulting transfer bond-stress distribution is shown in Figure 5. The calculated plastic transfer bond stress is 9,584 lbs/linear ft along a plastic transfer zone of 43.49 in. in length. The elastic transfer zone is 1.44 in. in length. The total force transferred is 423 kips.

Preliminary Finite-Element Grids

20. A series of generic preliminary finite-element grids were developed in order to arrive at a computationally efficient grid configuration to be used for the analysis. These grids included generic two-dimensional grids with plane-strain elements and axisymmetric grids. An initial grid geometry

was chosen to be 528 in. high and 24 in. wide with the anchor located vertically along the longitudinal axis of the grid. A plot of this grid is shown in Figure 6. To more effectively model the problem an axisymmetric grid configuration was used. The elements used in this grid were 4-node bi-linear axisymmetric elements from the ABAQUS element library. The basic geometry of this grid was the same as the two-dimensional grid discussed above.

Final Finite-Element Grid

21. After several iterations a final generic grid configuration was arrived at which would allow the bond stresses to be accurately modeled and still remain computationally efficient. This was an axisymmetric grid which was 264 inches high (1/2 the original grid height) and 24 inches in diameter. A two dimensional cross-sectional plot of this grid is shown in Figure 7 with a close up view of the critical region shown in Figure 8. Due to the symmetry of this section only the elements on one side of the longitudinal axis were generated. The centerline of the grid is on the left with the outer surface on the right. The anchor is a line of truss elements running along the axis. The secondary grout is modeled by the first column of elements, while the remainder of the elements represent the concrete. The boundary conditions used in the analysis were:

> (1) Free along the right side (outer surface),
> (2) Fixed in the horizontal direction along the axis
>   of symmetry,
> (3) Free along the upper surface,
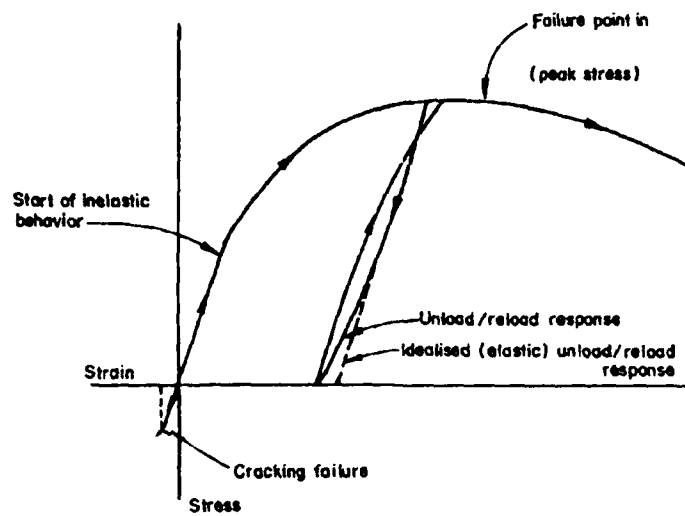> (4) Fixed in the vertical direction along the bottom.

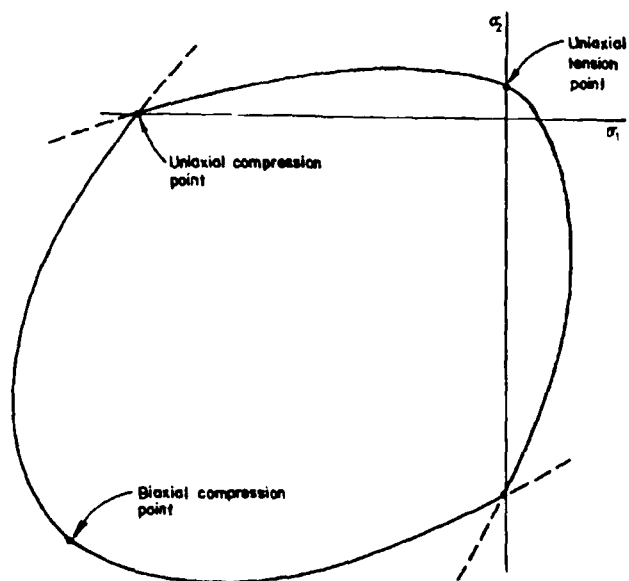Figure 2. Uniaxial behavior of plain concrete

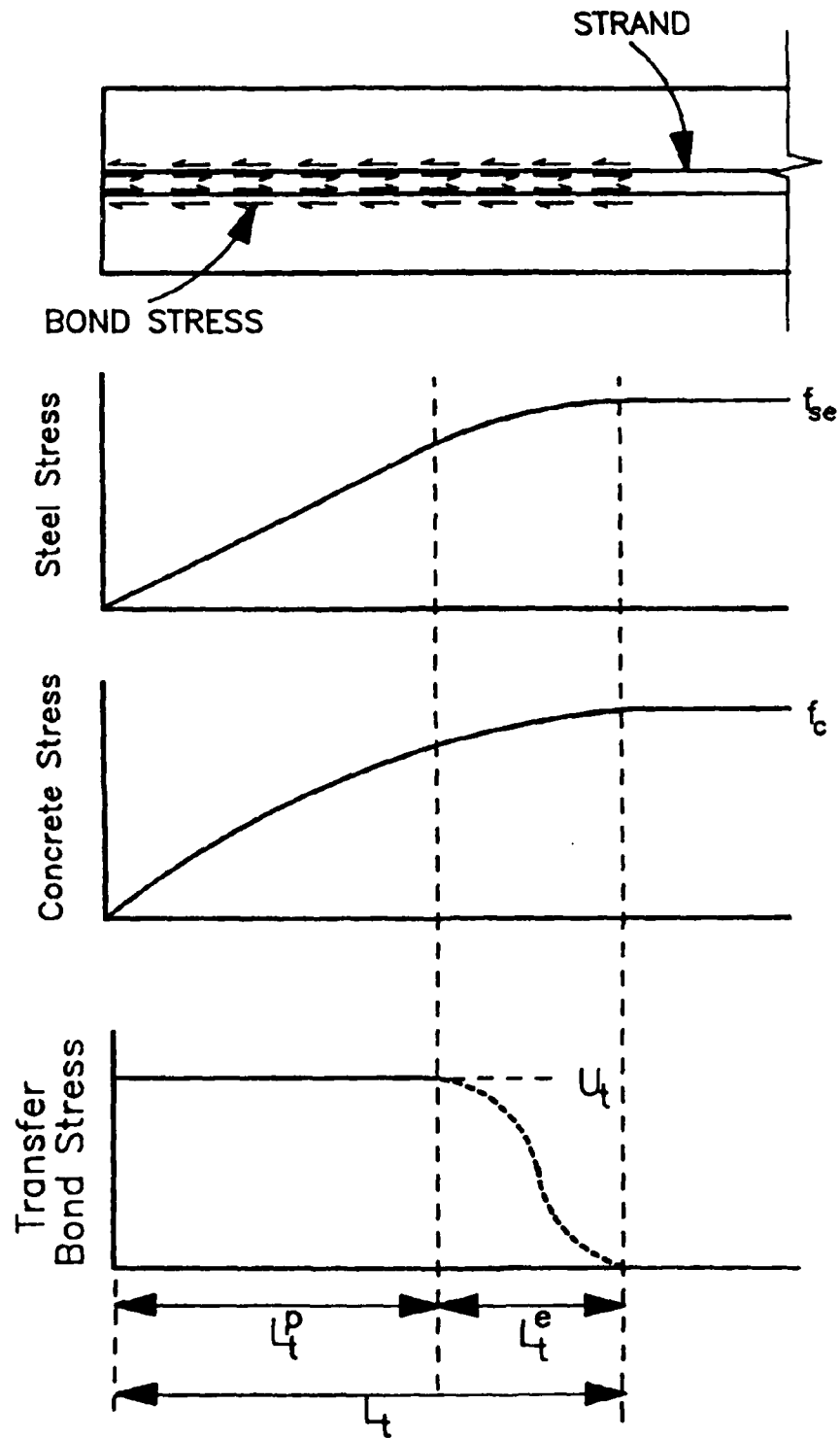Figure 3. Concrete failure data

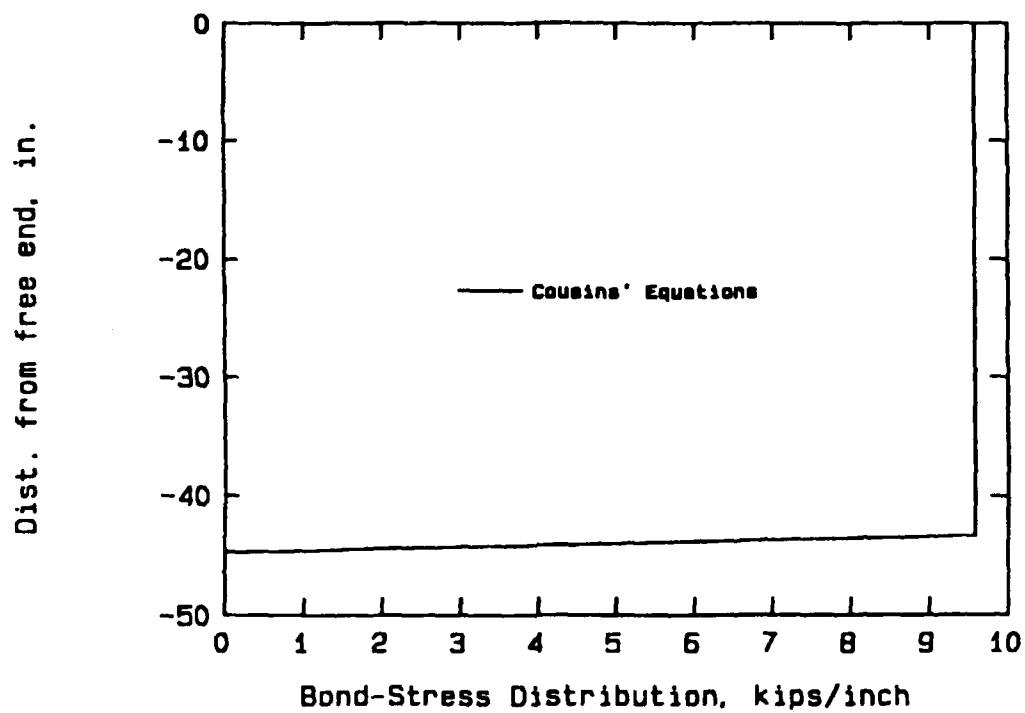Figure 4. Bond-transfer mechanism

Total Force = 423 kips
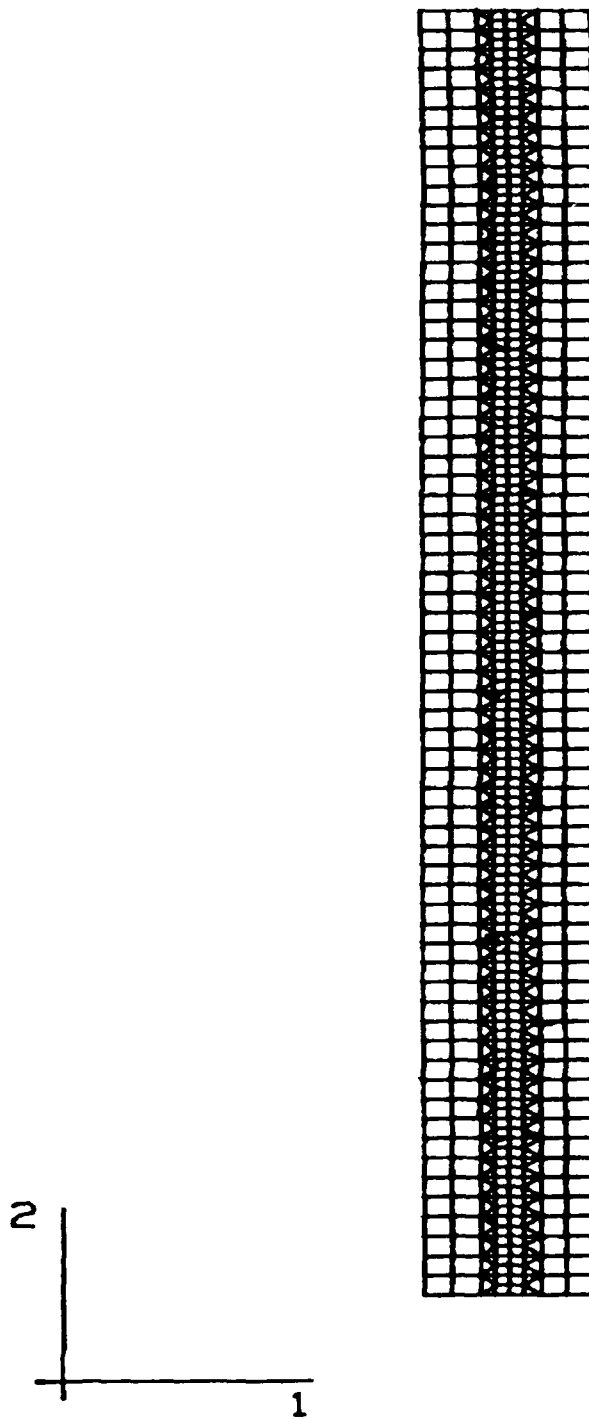

Figure 5.   Bond-stress distribution

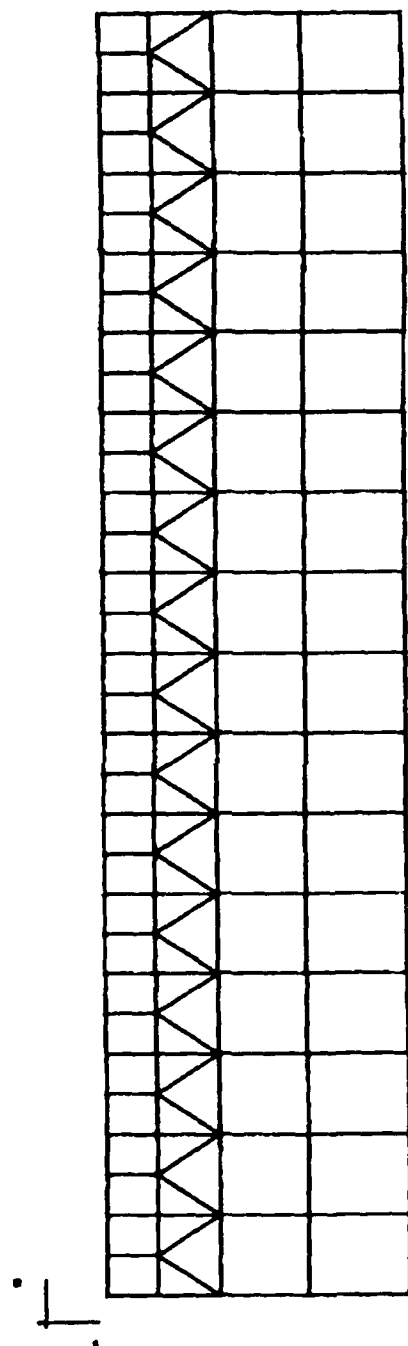Figure 6.   Preliminary two-dimensional finite-element grid

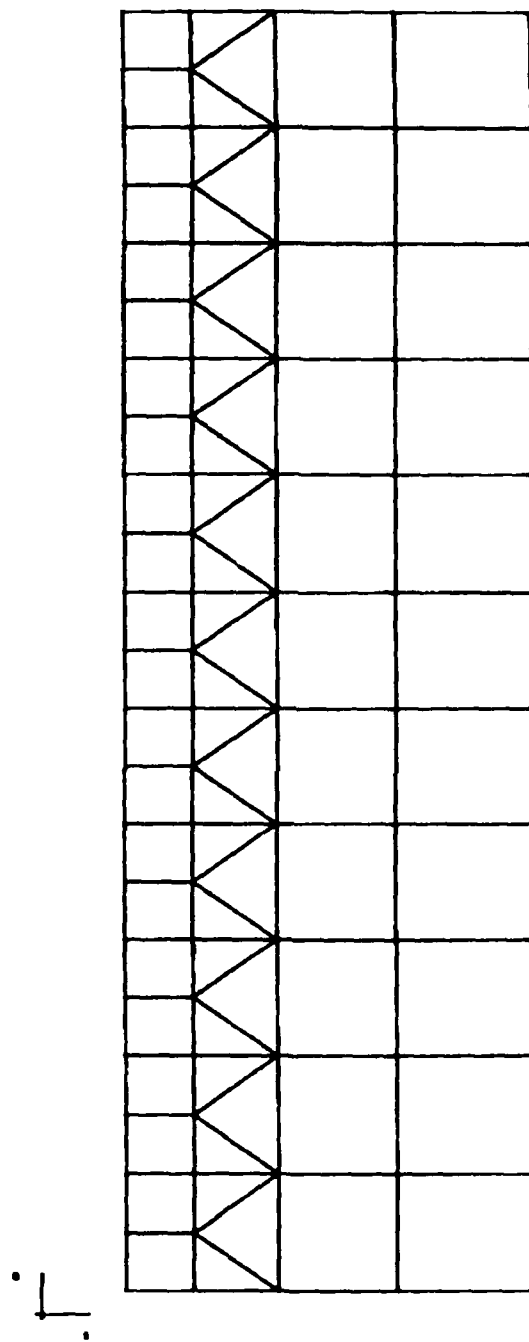Figure 7. Final axisymmetric finite-element grid

Figure 8. Detail view of critical region of final grid

PART IV: BOND-STRESS ANALYSIS

General

22. The analysis of the anchor bond-stress distribution was performed in two parts. A linear-elastic analysis was performed using the Cousins force distribution with the final axisymmetric grid. Following this a non-linear analysis was performed using the Chen and Chen plasticity model for the grout and concrete, and the same grid and loads as the linear-elastic analysis. The results of these analyses are presented in this chapter.

Presentation of Results

23. A linear-elastic finite-element calculation was performed on the final grid configuration with the Cousins bond-stress distribution as presented in Part III. The results of this analysis are shown as a contour plot of shear stress in Figure 9 with an expanded view of the critical region in Figure 10. The grout-concrete interface is shown as a vertical line denoted on the contour plot.

24. A non-linear finite-element analysis was performed on the final generic grid configuration with the Cousins bond-stress distribution. In this analysis, the Chen and Chen plasticity model available in ABAQUS was used to model the concrete and grout. The results of this analysis are also shown as a contour plot of shear stress in Figure 11 with an expanded view of the critical region shown in Figure 12. The concrete-grout interface is denoted by the vertical line shown on the contour plot.

Discussion of Results

23. The contour plots of shear stress from both the linear and non-linear analyses show approximately the same results. The maximum shear stress in the section is on the order of 850 psi in both analyses. The maximum shear stress occurs in the secondary grout along the length of the anchor. The 4,500-psi grout used to bond the anchors would have a shear strength in the 2,000-2,250

psi range. The maximum shear stresses along the grout-concrete interface are in the 450-500 psi range, which is well within the estimated bond strength of 1,200-1,500 psi. The shear stresses in the concrete range from 0 to 500 psi, which is also well below 1,000 psi which is the estimated shear strength of the concrete. The distribution of these stresses are shown in Figure 13 and Figure 14. These stress values were taken from the concrete elements nearest the concrete-grout interface and from the integration points nearest the loaded face of the grout elements.
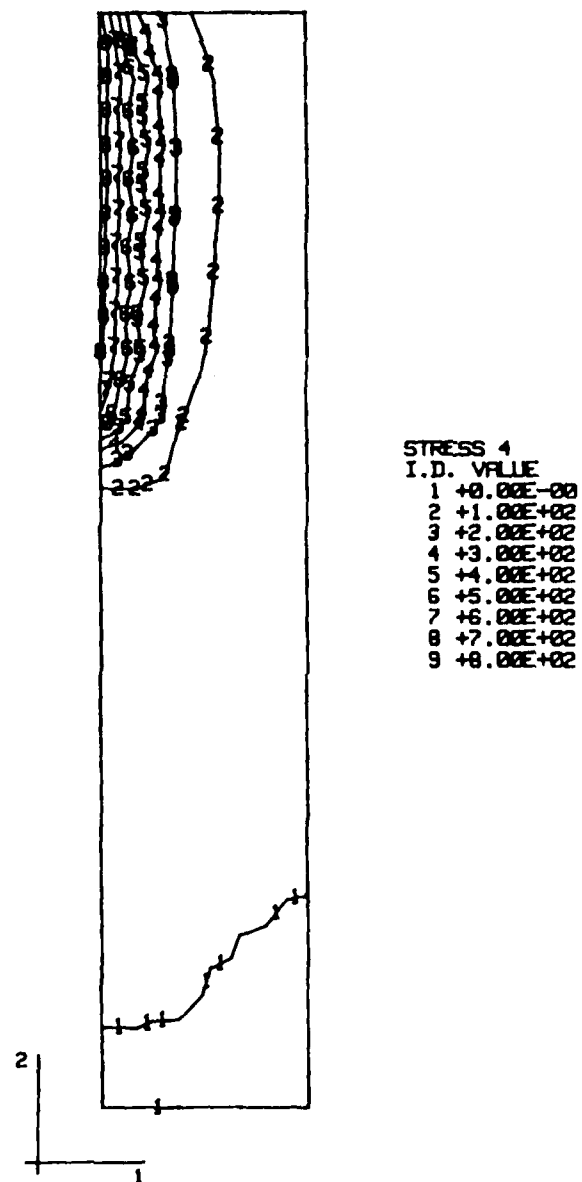
STRESS 4
I.D. VALUE
1 +0.00E-00
2 +1.00E+02
3 +2.00E+02
4 +3.00E+02
5 +4.00E+02
6 +5.00E+02
7 +6.00E+02
8 +7.00E+02
9 +8.00E+02

Figure 9. Shear-stress contours in psi from linear-elastic analysis

STRESS 4
I.D. VALUE
1 +0.00E-00
2 +1.00E+02
3 +2.00E+02
4 +3.00E+02
5 +4.00E+02
6 +5.00E+02
7 +6.00E+02
8 +7.00E+02
9 +8.00E+02
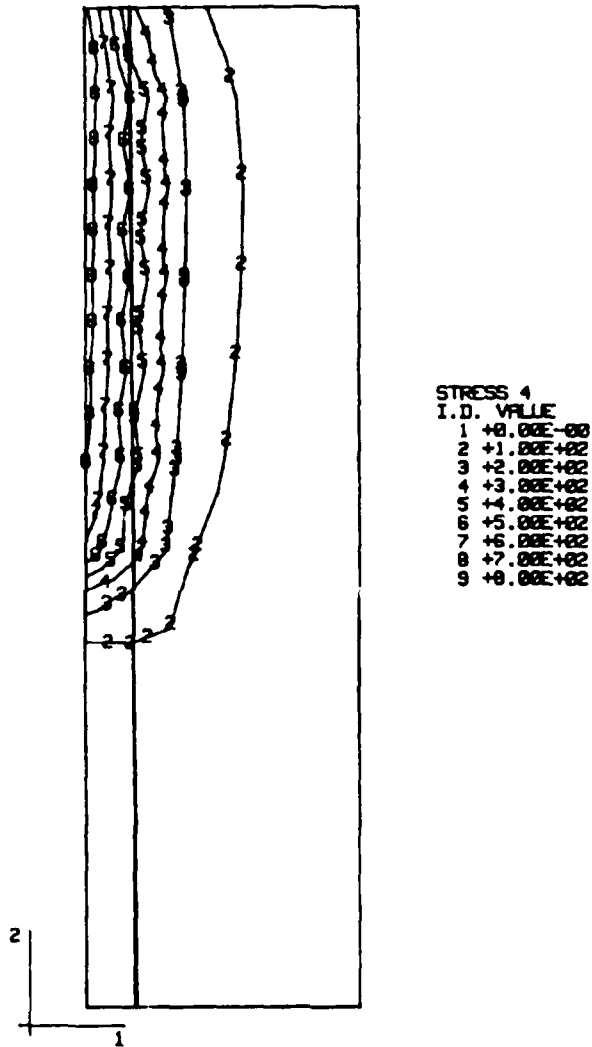
Figure 10.   Detail view of shear-stress contours in psi
             from linear-elastic analysis

STRESS 4
I.D. VALUE
1 +0.00E-00
2 +1.00E+02
3 +2.00E+02
4 +3.00E+02
5 +4.00E+02
6 +5.00E+02
7 +6.00E+02
8 +7.00E+02
9 +8.00E+02
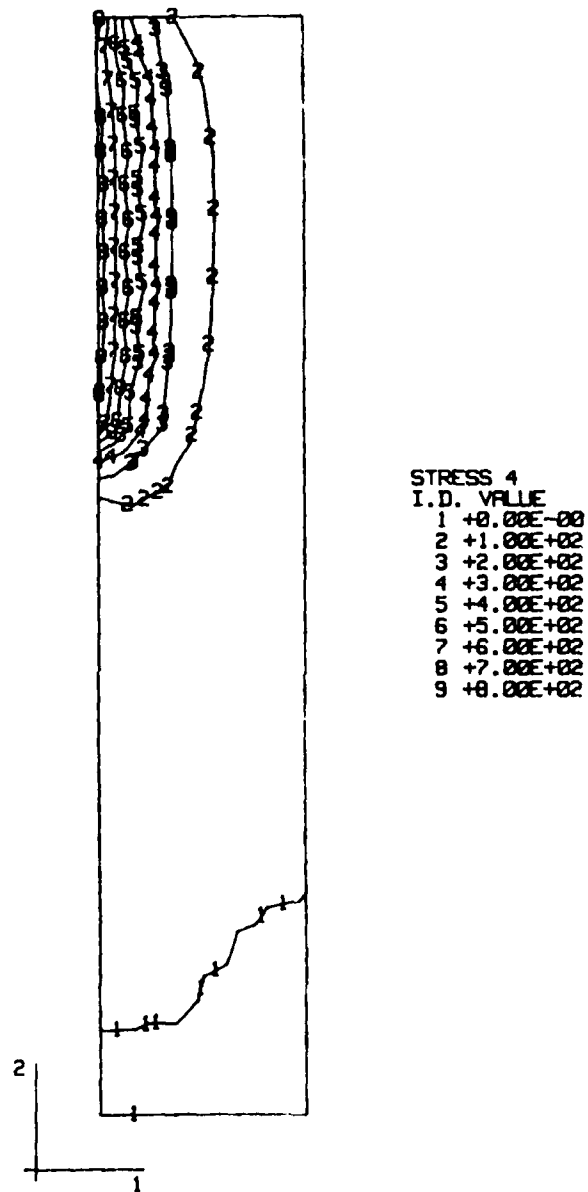
Figure 11.   Shear-stress contours in psi from non-linear analysis

STRESS 4
I.D. VALUE
1 +0.00E-00
2 +1.00E+02
3 +2.00E+02
4 +3.00E+02
5 +4.00E+02
6 +5.00E+02
7 +6.00E+02
8 +7.00E+02
9 +8.00E+02
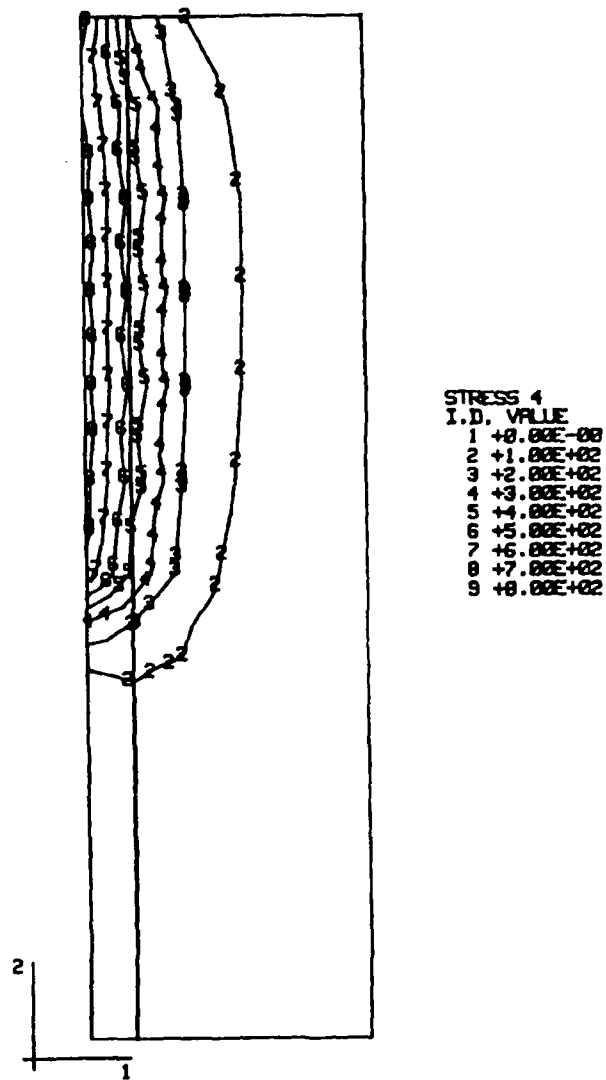
Figure 12.   Detail view of shear-stress contours in psi
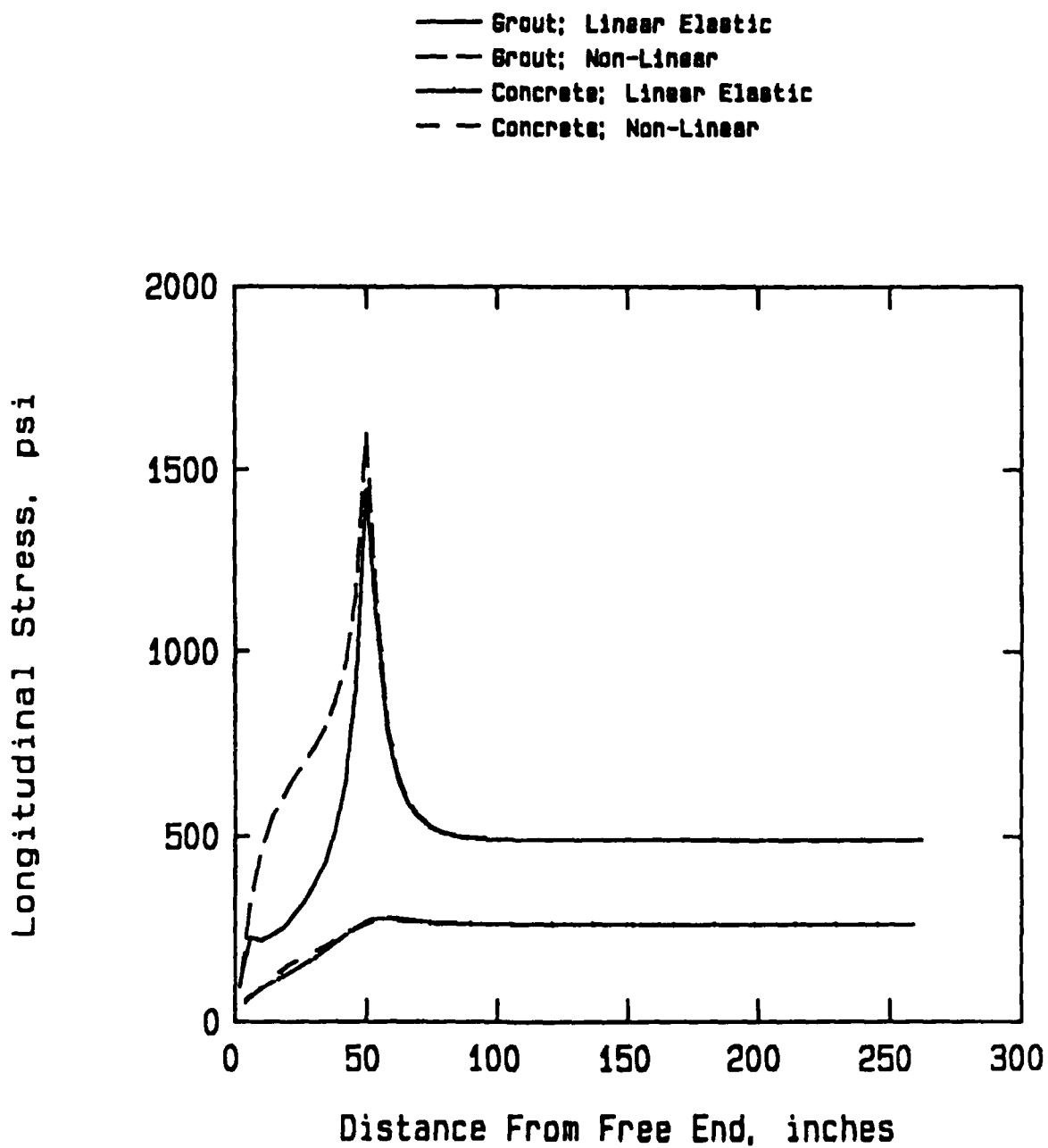from non-linear analysis

Figure 13. Longitudinal compressive-stress distribution
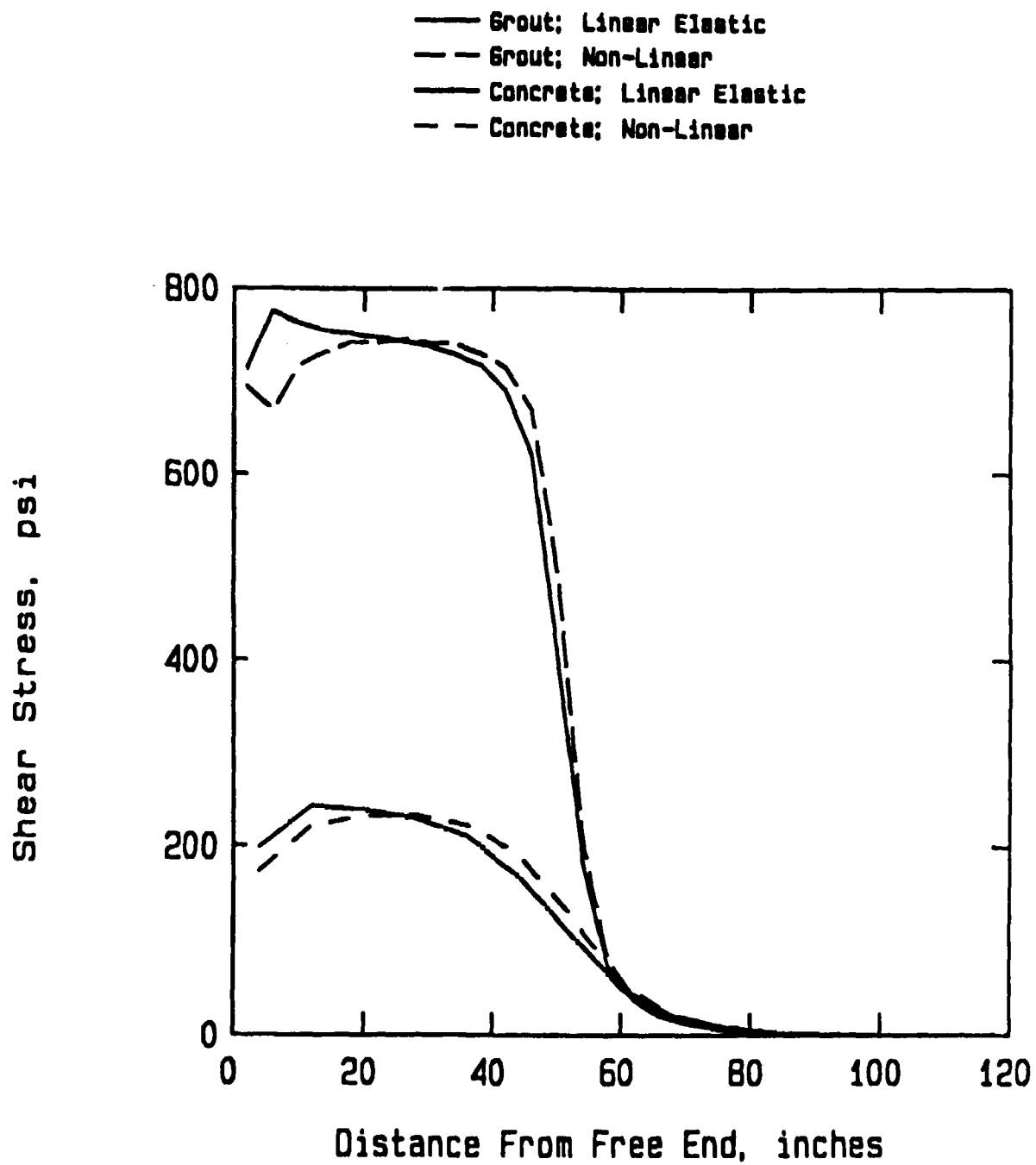
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Figure 14. Shear-stress distribution

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PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

26. Based on the results of the survey of recent developments in the state-of-the-art of posttensioned anchor bond-stress calculation, the equations proposed by Cousins, et al, were used to predict the bond-stress distribution along the secondary grouted anchors. This method of calculation was chosen because of its ability to compute both the magnitude and longitudinal distribution of bond stresses. The results of the finite-element analyses presented in PART IV clearly show that the bond-force equations used provide a rational and consistent method for predicting bond-force distribution. The analyses show that neither the estimated compressive strength of the grout and concrete nor the estimated shear strength along the grout-concrete interface were exceeded.

Recommendations

27. Because this method of stabilizing gravity structures is becoming more frequently used by the Corps and other owners of gravity structures, additional work should be conducted to develop improved analysis procedures. Additional effort is recommended in both the experimental and computational areas. An extensive survey of available experimental data should be conducted to identify critical response features necessary for analytical model development. A comprehensive experimental program should then be performed to study the behavior of grouted anchors in gravity structures. These data should be used to develop and verify improved analytical models of steel-grout-concrete interaction suitable for inclusion in general purpose finite-element codes. These models should address both bond-slip behavior (including transfer bond stresses and bond-transfer lengths) and dowel action.

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